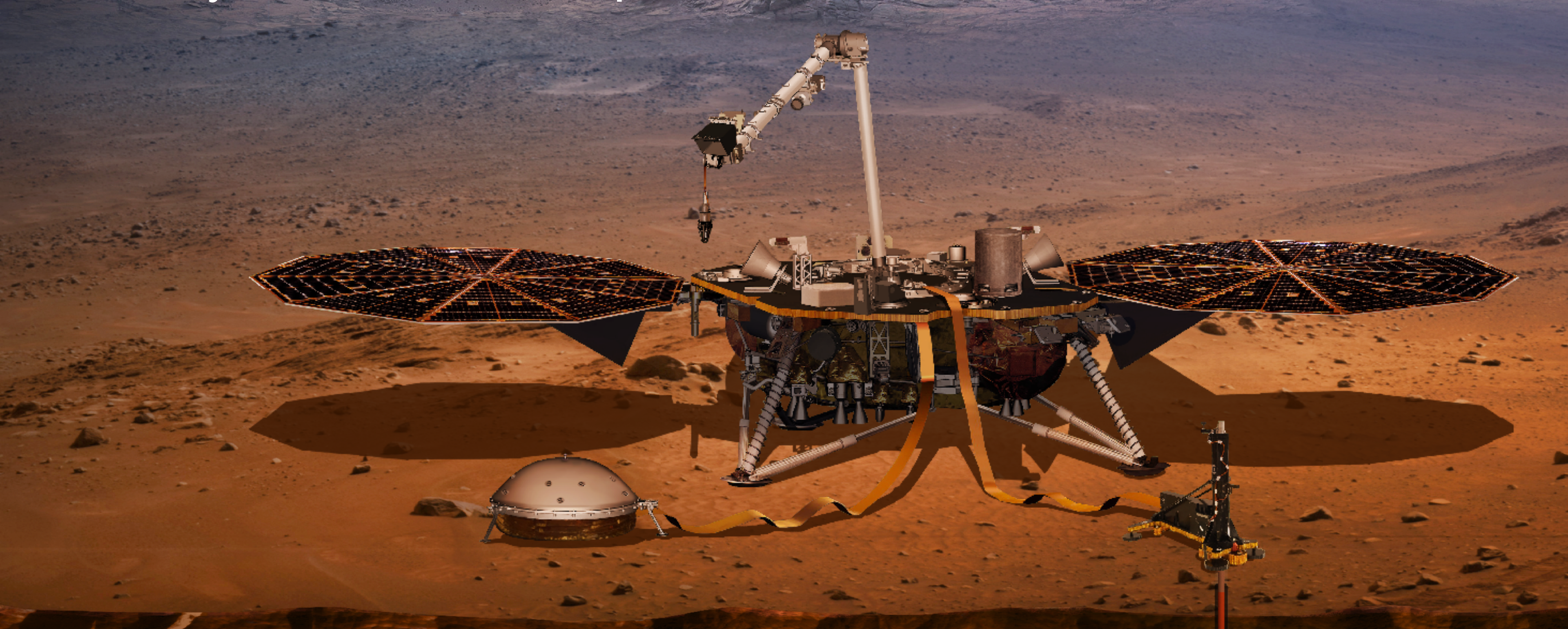
InSight: Interior Exploration using Seismic Investigations, Geodesy and Heat Transport



Successfully Navigating InSight to Mars

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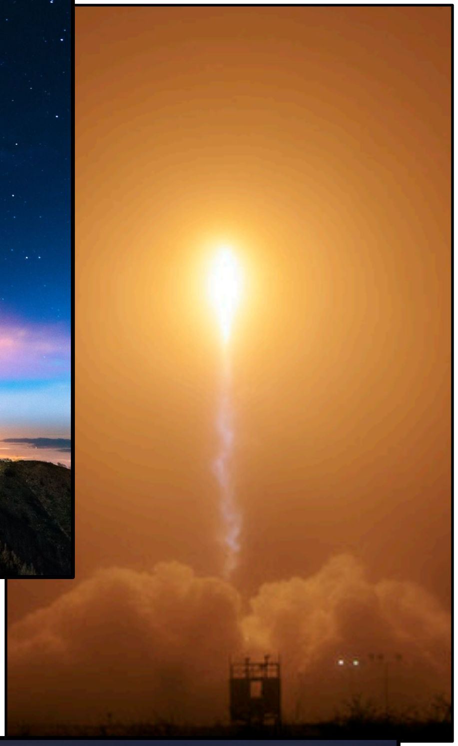
University of Colorado at Boulder

March 20, 2019

Agenda

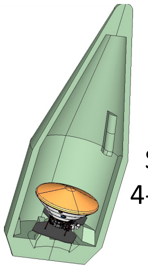
- Mission Overview
- Spacecraft Details
- Navigation Basics
- Cruise Highlights



Mission Overview

LAUNCH

May 5, 2018
(first opportunity)



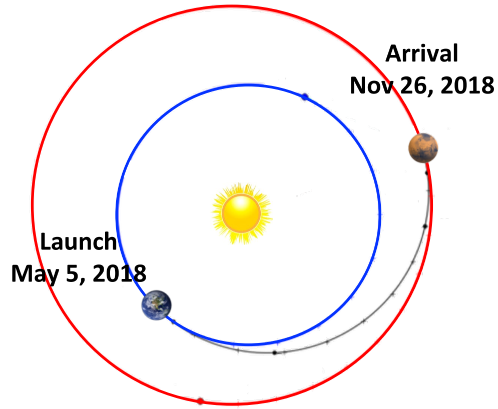
InSight
Stowed in
4-m Payload
Fairing

Vandenberg Air Force Base
(Western Test Range)

Atlas V 401

INTERPLANETARY CRUISE

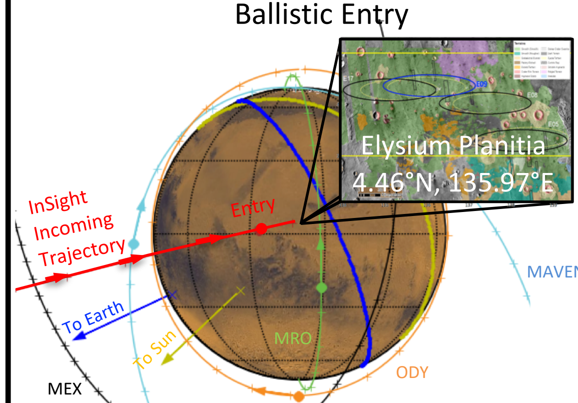
205 days



Type 1 Trajectory
Max C_3 = 14.3 km^2/s^2, max DLA = -40.8 deg

APPROACH & EDL

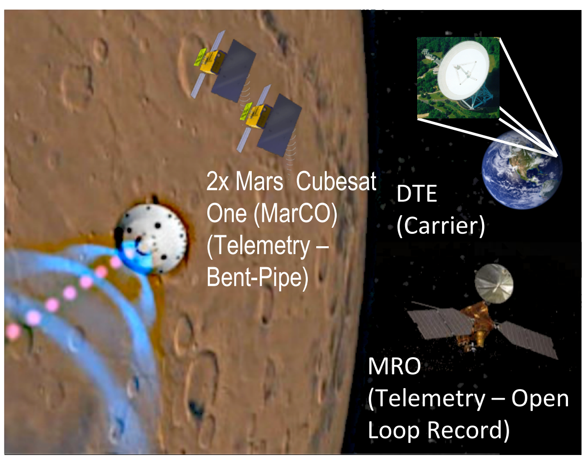
Ballistic Entry



Max. Entry Speed = 5.63 km/s (relative)
Ls = 296 deg (dust storm season)
Landing elevation ~ -2.7 km
Landing LMST ~2:52 PM

EDL COMMUNICATIONS

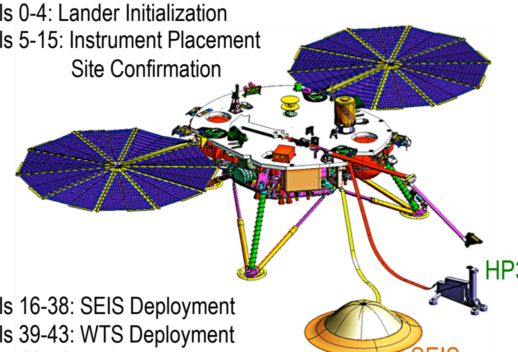
Ultra-High Frequency Link



DEPLOYMENT

54 Sols

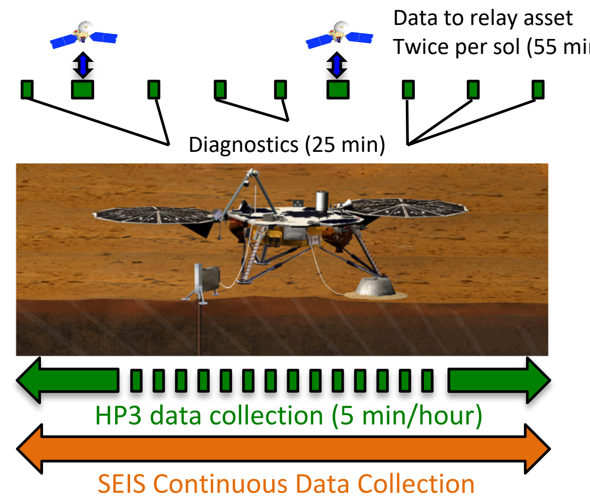
Nominal Plan:
Sols 0-4: Lander Initialization
Sols 5-15: Instrument Placement
Site Confirmation



Sols 16-38: SEIS Deployment
Sols 39-43: WTS Deployment
Sols 44-54: HP3 Deployment
Sols 55-98: HP3 Hammering
Sols 99-709: Science Monitoring

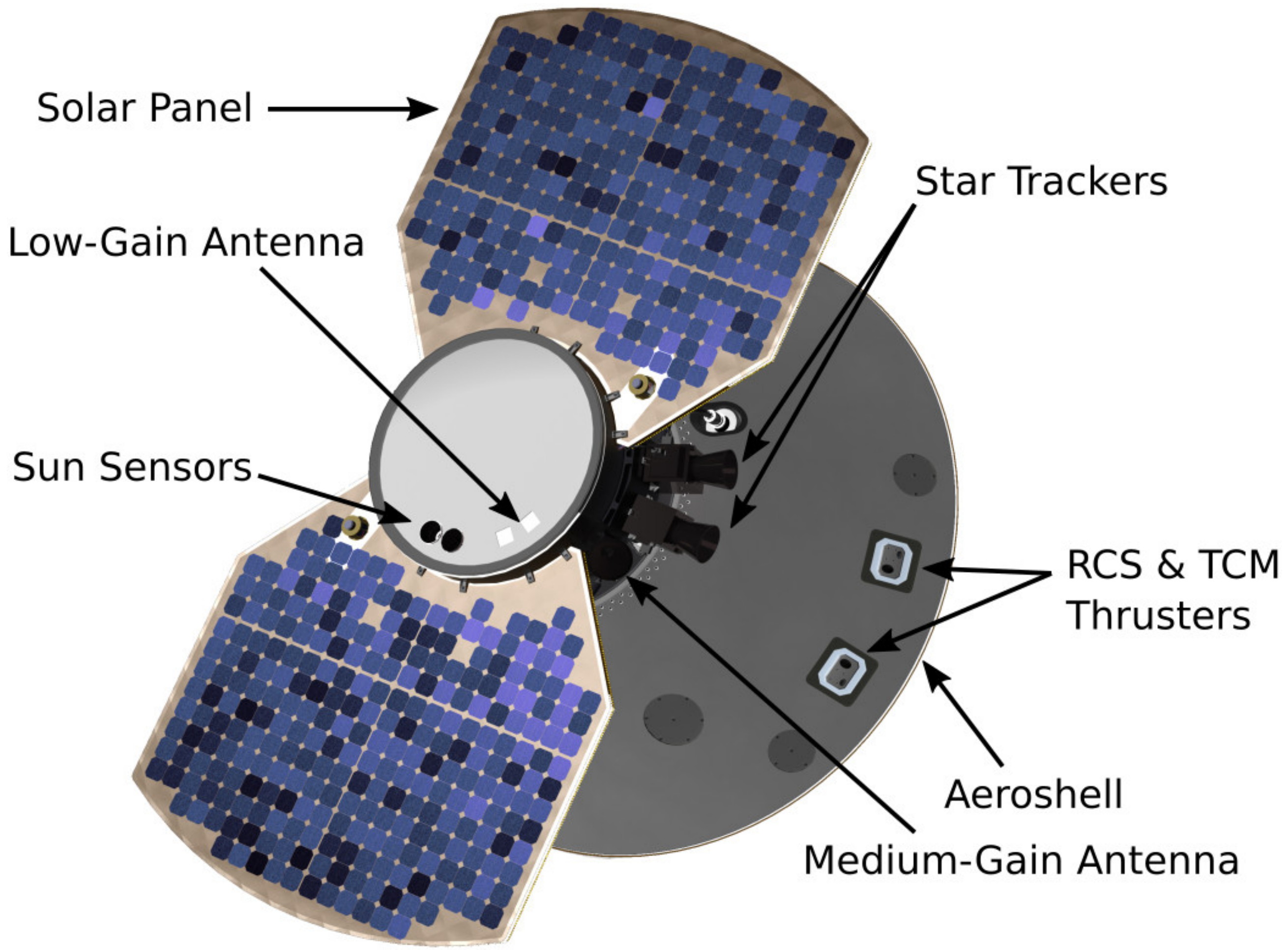
SCIENCE MONITORING

One Martian Year (sol 99 – sol 709)



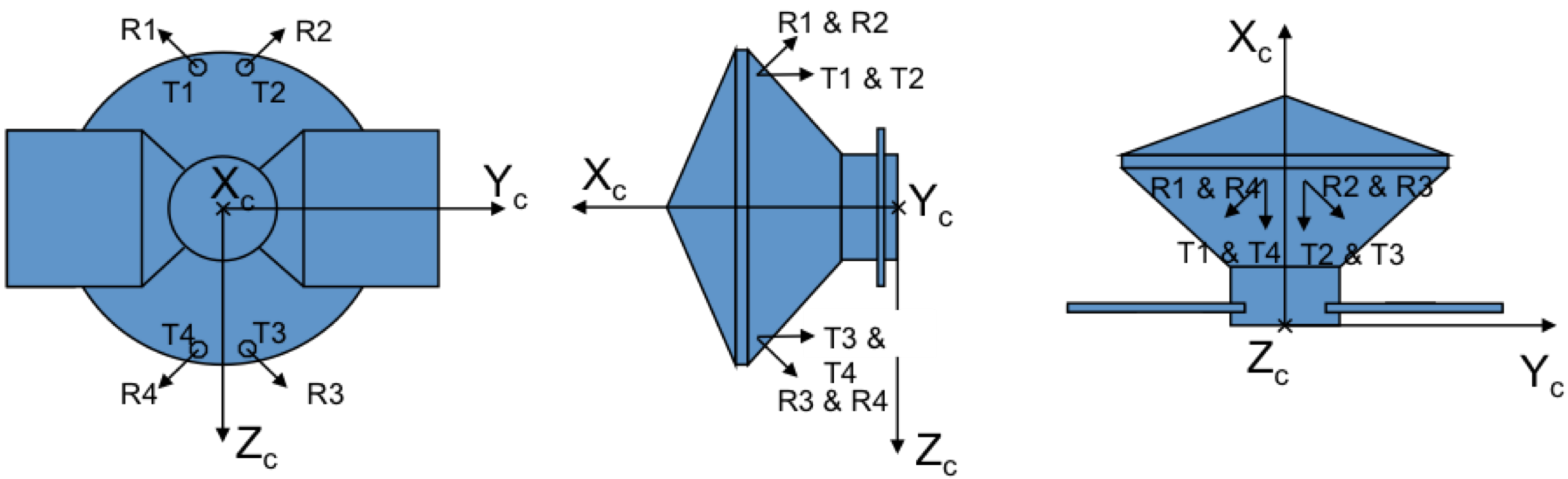
The InSight Spacecraft (Cruise Stage)

- Phoenix heritage spacecraft built by Lockheed-Martin



Attitude Control System (ACS)

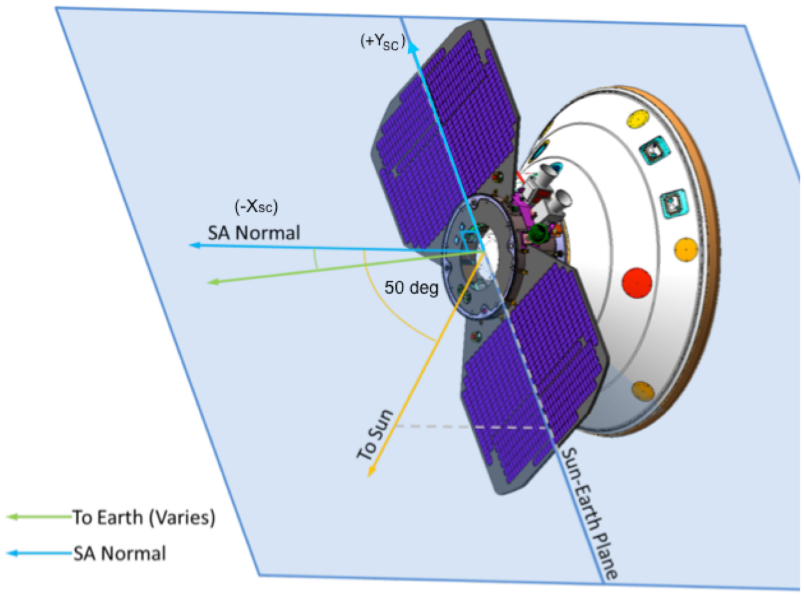
- Attitude control provided via an unbalanced thruster system
  - 4 Reaction Control System (RCS) thrusters fire in pairs for 3-axis stabilization & slew to/from TCM attitudes
- 4 Trajectory Correction Maneuver (TCM) thrusters execute main burns
- RCS/TCM thrusters mounted onto lander & extended through backshell
  - Scarfed to backshell contour
  - Each RCS thrust vector had non-zero component in all 3 axes



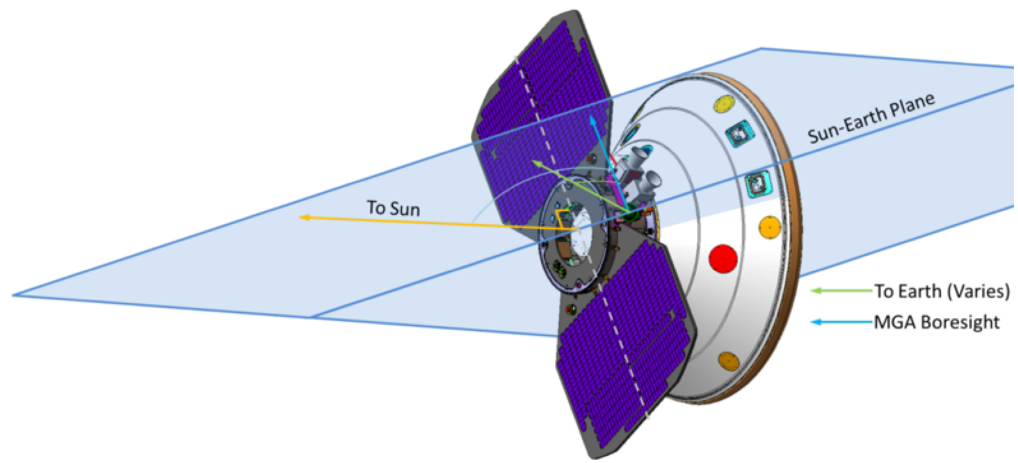
Cruise Attitude Profiles

- Two attitude profiles designed to balance power, communications, and thermal constraints throughout cruise

Early Cruise: Launch to July 12



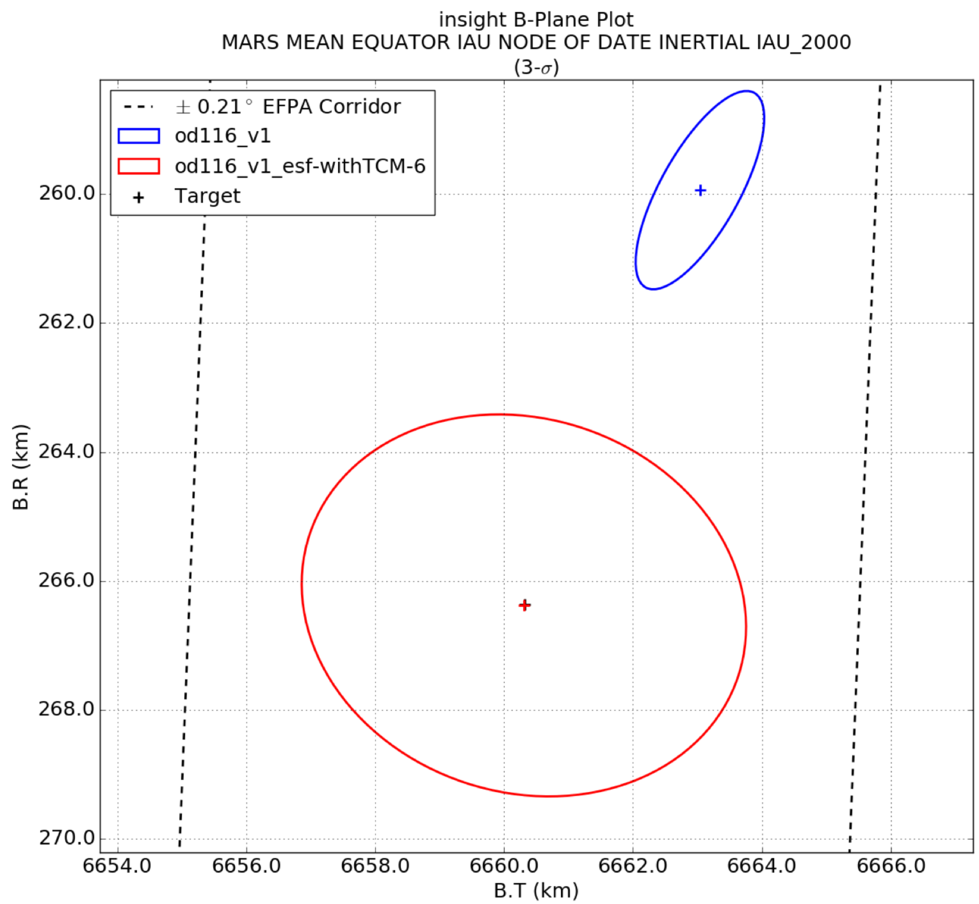
Late Cruise: July 12 to Entry



- Attitude maintained via deadbanding
  - Early cruise: 3-axis RCS ΔV due to off-Sun pointing
  - Late cruise: Y and Z nominally balanced, RCS ΔV in X direction
  - In reality, thrusters not perfectly balanced, small ΔVs in Y and Z also

Navigation Basics

- Determine the spacecraft state
- Predict the future trajectory
- Quantify the uncertainty associated with those estimates
- Design maneuvers to aim for the target
- Two driving navigation requirements:
  - Deliver s/c to atmospheric entry at an entry flight path angle of -12.0 deg +/- 0.21 deg (3-**σ**)
  - Estimate entry flight path angle to within 0.15 deg for final onboard state update



Example B-Plane

Orbit Determination Data

- 1) Radiometric tracking data (Deep Space Network, DSN)
  - Doppler
  - Range
  - Delta-Differential One-way Range (ΔDOR)
- 2) Spacecraft telemetry
  - Channelized data
    - Routine telemetry available during communication passes
    - Attitude, angular rates, temperatures, pressures, etc.
  - Non-channelized data
    - Small Force Data packets: time of firing, valve on-time, attitude at time of firing
    - Created every time a thruster fired, stored onboard, downlinked when possible
  - Interspersed these two data types for attitude modeling
  - OD team directly queried telemetry servers

Spacecraft & Measurement Modeling

- Small forces
  - Time-varying attitude using downlinked telemetry
  - Impulsive burn for every RCS thruster pulse
- Antenna motion (part of modeling attitude)
- Solar Radiation Pressure (SRP)
  - Spherical harmonics expansion per axis (4 coefficients/axis)
  - Can capture very complex SRP forces
  - Simpler and more flexible than Phoenix approach of modeling spacecraft components
- Spacecraft state, maneuvers, media effects, Earth polar motion, UT1 bias, DSN station locations, quasar locations, gravitational parameters, Earth/Mars ephemerides…

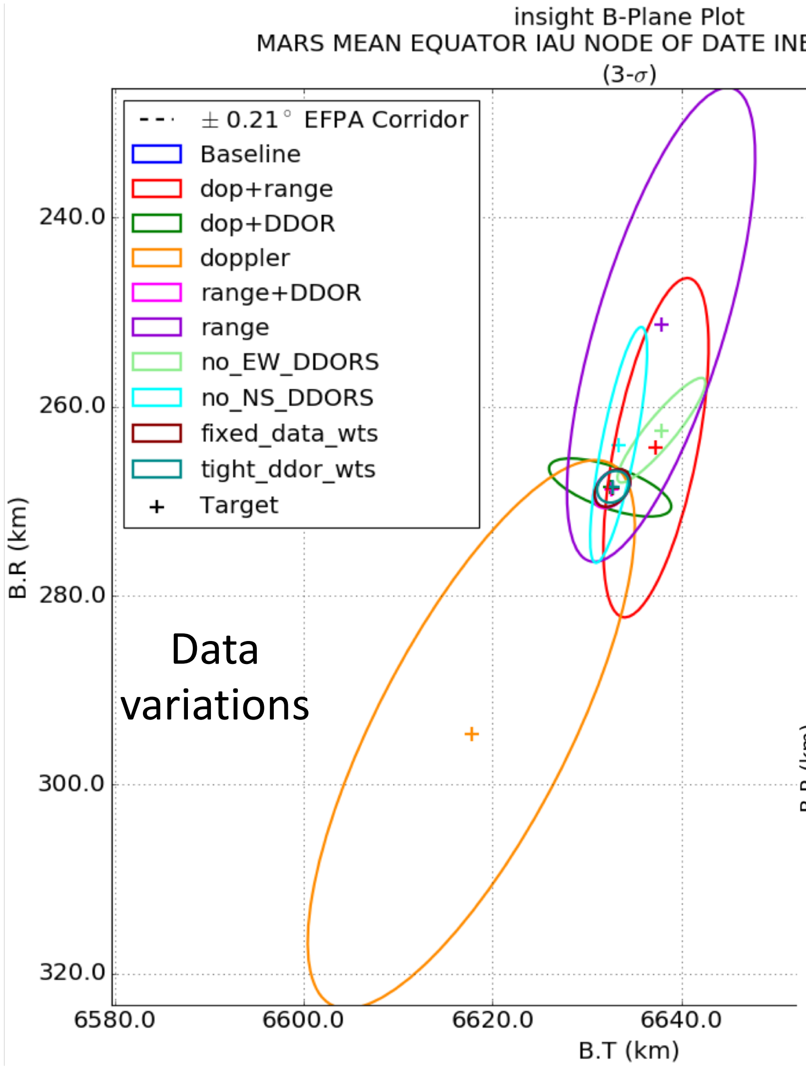
Linear Kalman Filter – Baseline Configuration

Error Source	Estimation Model	*A Priori* Uncertainty	Comments
Spacecraft Position	Dynamic	3 km	Sun-centric EME2000
Spacecraft Velocity	Dynamic	3 m/sec	Sun-centric EME2000
2-way Doppler noise	-	$\geq$ 0.05 mm/sec	
2-way Range noise	-	$\geq$ 1 m	
ΔDOR noise	-	60 ps	
2-way Range Bias	Stochastic	2 m	Uncorrelated per-pass
TCM & TCM Slews	Bias	Requirement Gates Model	
Thrust Direction Y Offset	Bias	3°	
Thrust Direction Z Offset	Bias	3°	
ΔV Magnitude	Bias/Stochastic	3%/15%	Uncorrelated per-firing
SRP Scale Factor	Bias	10%	
SRP Spherical Harmonics	Bias	1 m^2	Early & late cruise biases
Ionosphere Day/Night	Consider	55/15 cm	Per DSN complex
Troposphere Wet/Dry	Consider	1/1 cm	Per DSN complex
Earth Polar Motion (ΔX/ΔY)	Consider	1/1 cm	
UT1 Bias	Consider	2 cm	
DSN Station Locations	Consider	2003 Covariance	Reference 8
Quasar Locations	Consider	1 nrad	
Mars Gravitational Parameter	Consider	$2.8e^{-4}$ km^3/sec^2	
Earth Gravitational Parameter	Consider	$1.4e^{-3}$ km^3/sec^2	
Moon Gravitational Parameter	Consider	$1.0e^{-4}$ km^3/sec^2	
Earth-Mars Ephemeris	Consider	DE423 Covariance	Reference 9
Deimos Ephemeris	Consider	[3, 5, 3] km	Deimos-fixed frame
Phobos Ephemeris	Consider	[2, 5, 2] km	Phobos-fixed frame

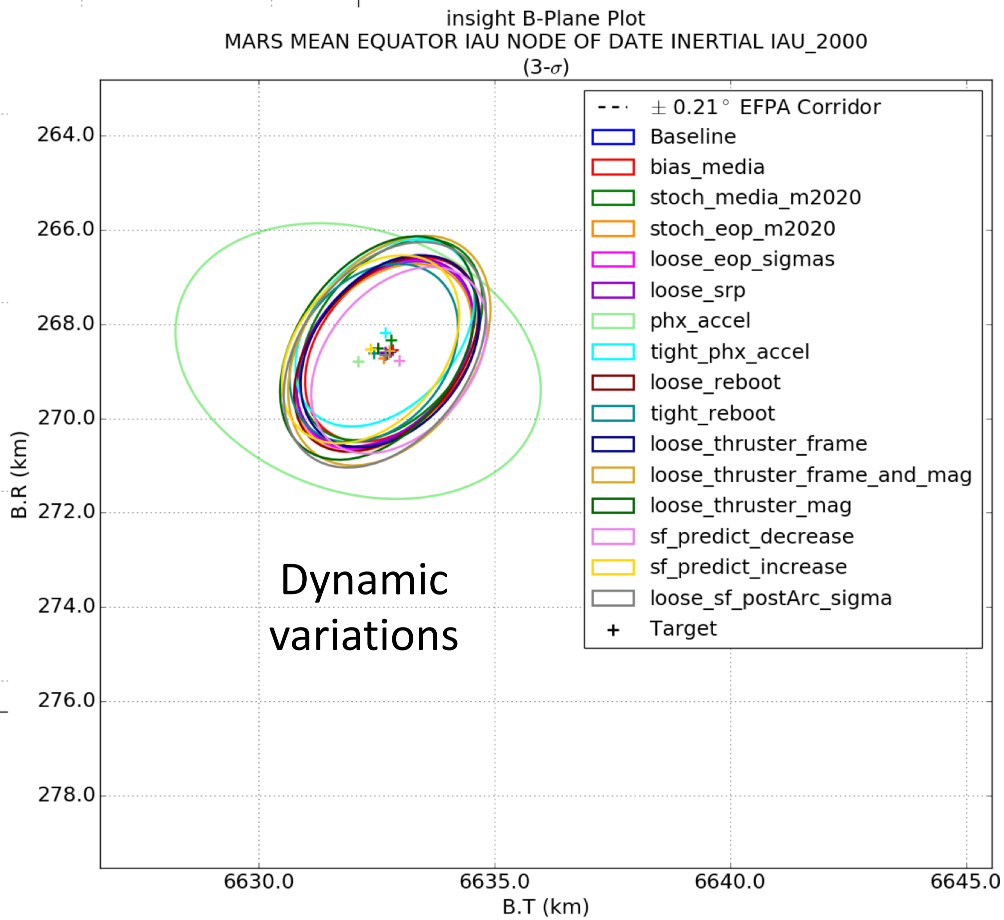
(DSN Station Updates for MER)

(Mars Ephemeris Uncertainty for MSL)

Many, many filter variations to assess sensitivities



Not shown: variations of data arc lengths



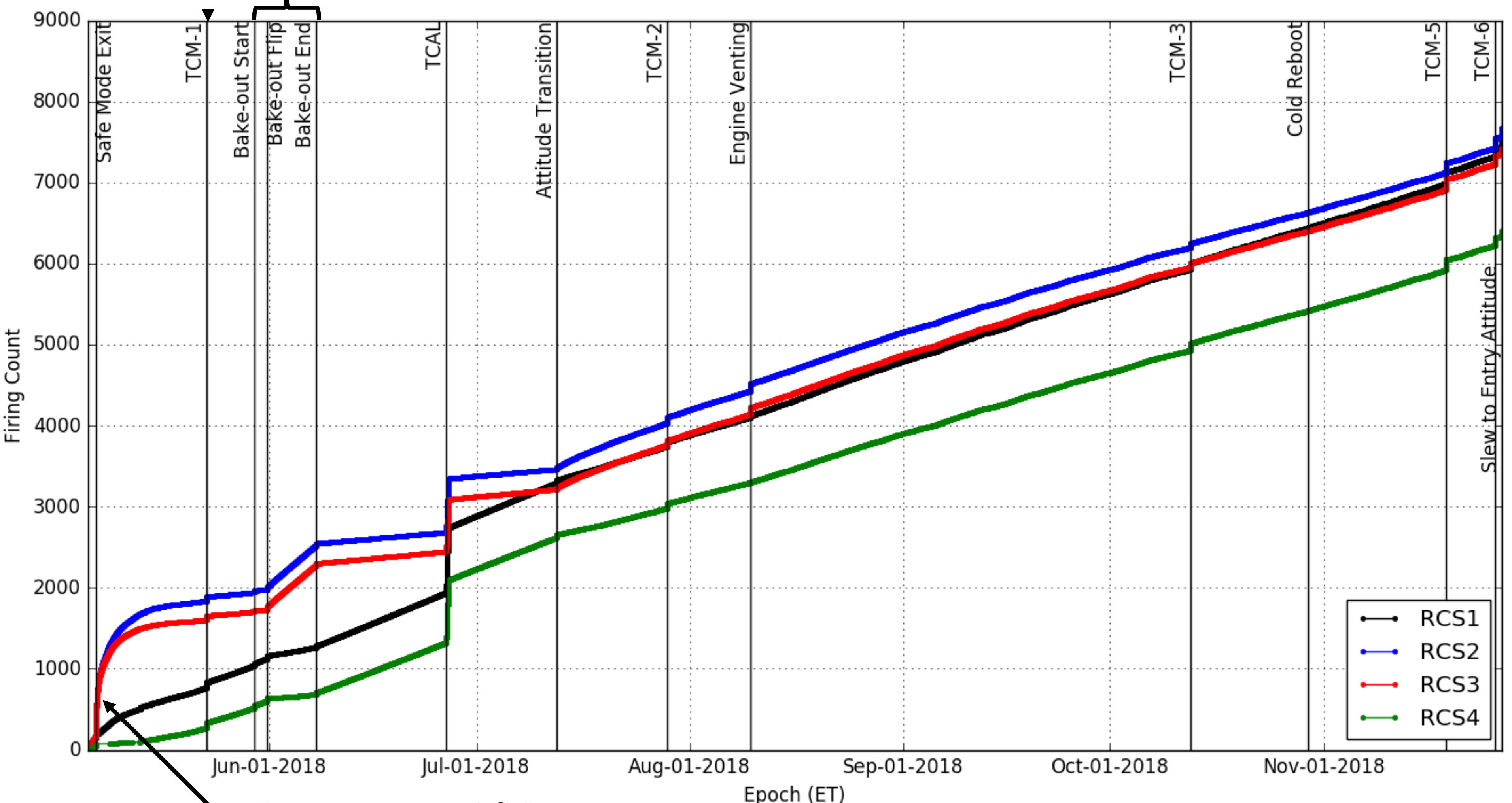
Launch and Early Cruise

- Launch OD is “quick and dirty”
  - Simplified models, polynomial accelerations as surrogate for discrete small forces
  - Limited scope of OD: ensure acquisition at next DSN station
  - Short (1.5 hour) Goldstone pass meant no OD update was available for Canberra acquisition
- Within several hours of launch, significant non-gravitational accelerations were detectable
- Switching to modeling discrete firings with telemetry helped
- Leading hypothesis: outgassing as components were exposed to the Sun
- No bakeout performed on the ground prior to 2018 launch

RCS Thruster Flight Performance

TCM-1 postponed

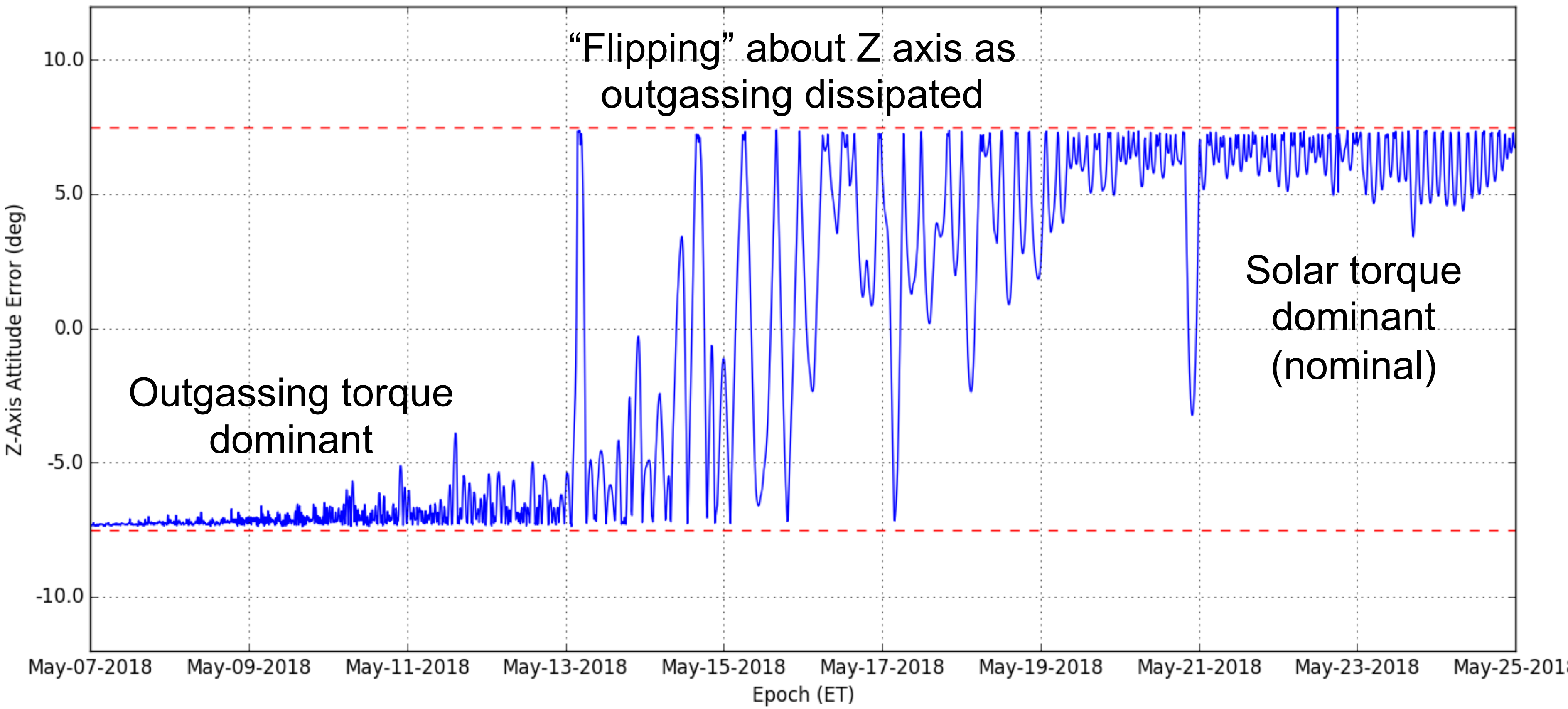
In-flight bakeout



~25x expected firing rate due to outgassing

Attitude Errors During Heavy Outgassing (May 2018)

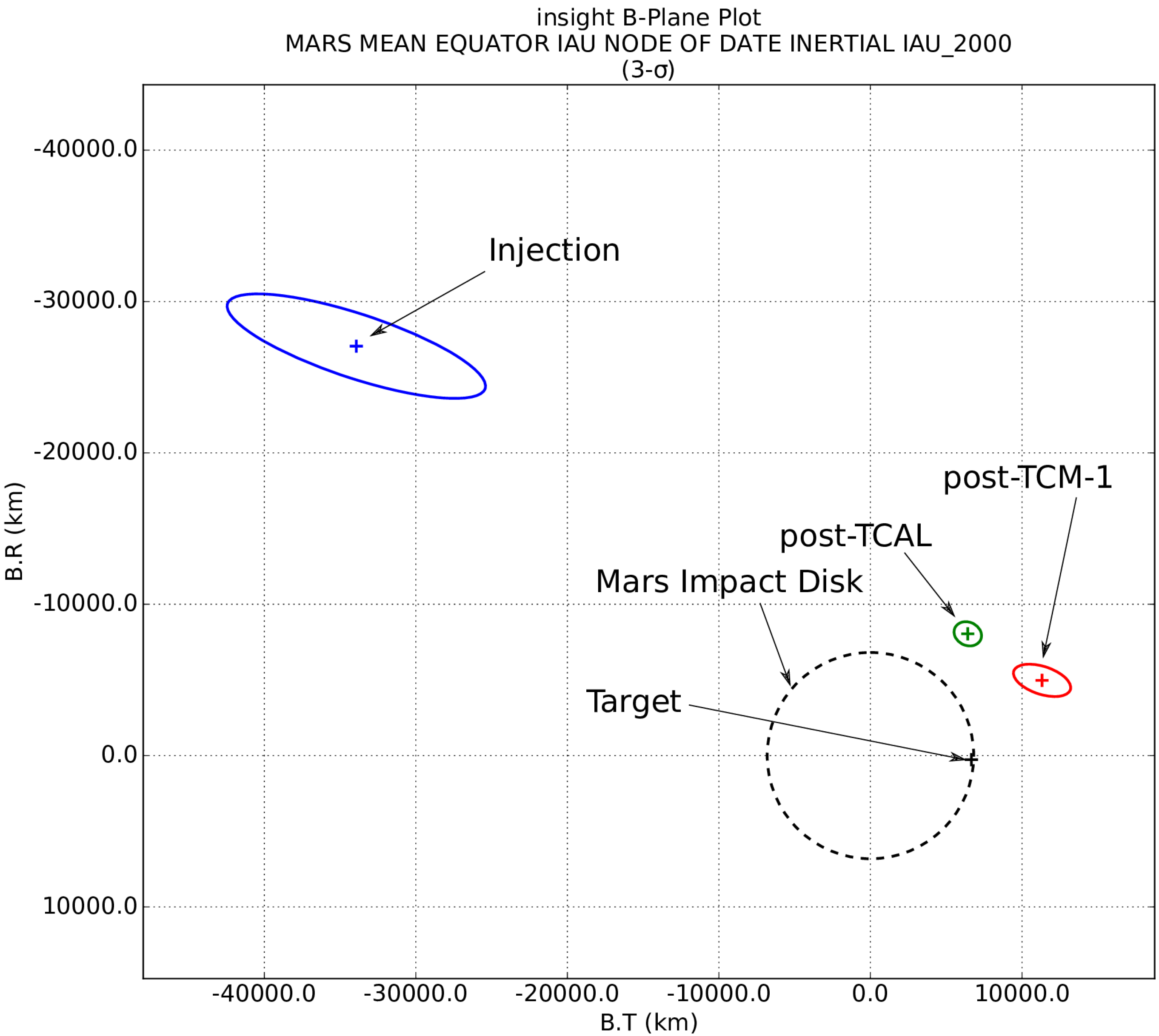
- Outgassing torque pinned spacecraft against the -Y, -Z deadbands
- Outgassing and solar pressure torques acted in opposite directions
  – Solar torque effect not observable until outgassing dissipated



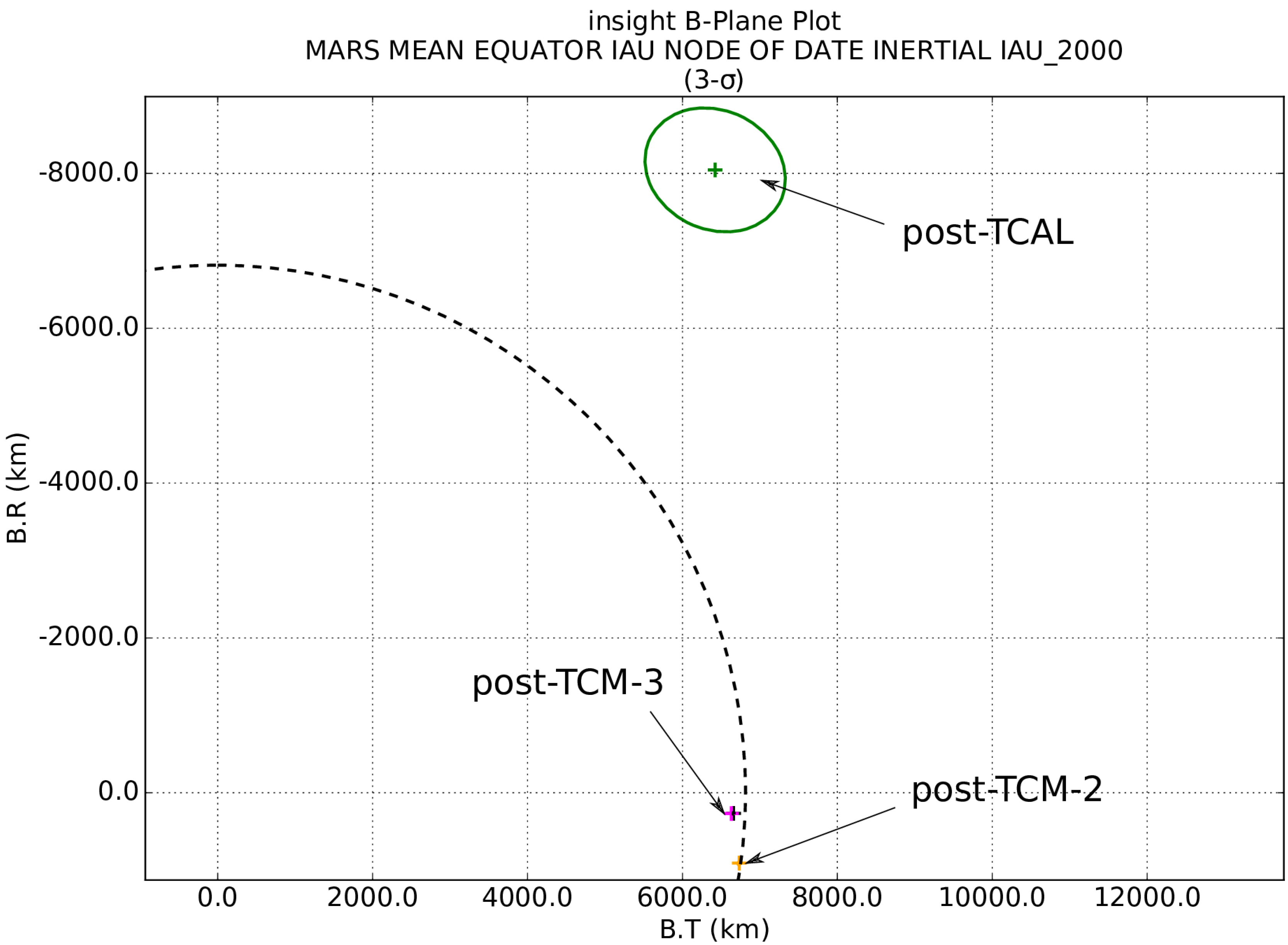
Project-Level Outgassing Response

- TCM-1 delay
  - Plan: data cutoff (DCO) at L+5 days, execution at L+10 days
  - Flight: DCO at L+10 days, execution at L+17 days
- TCM-1/2 combination
  - Plan: Use TCM-1 to target the entry point directly
  - Flight: Optimize TCM-1 jointly with TCM-2 to split the ΔV between the two maneuvers
  - Allowed us to prevent wasting propellant used at TCM-1, knowing that outgassing was still happening
- Unplanned in-flight "bakeout" activity
  - Put spacecraft in two attitudes used during the RCS thruster calibration (TCAL) to ensure outgassing torque wouldn't interfere with the TCAL

B-plane: Injection to TCAL

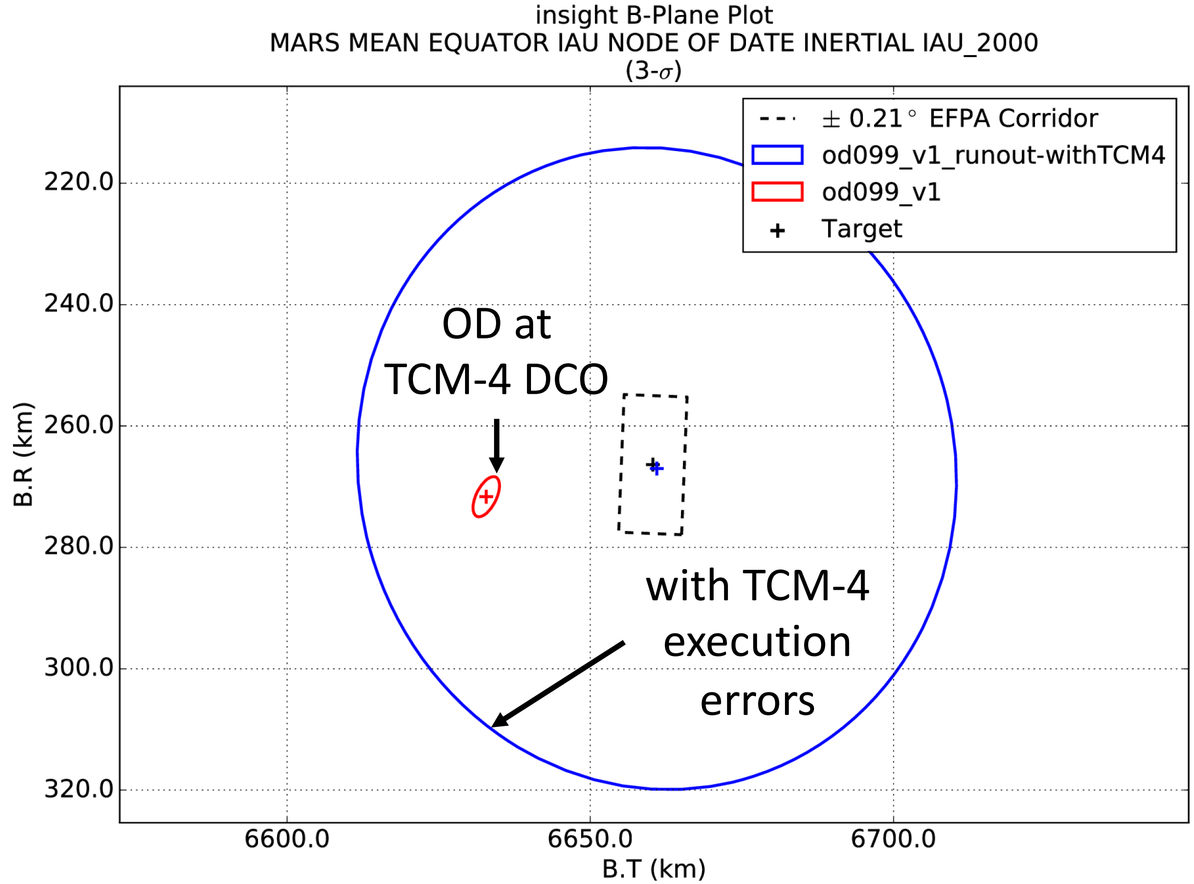


B-plane: TCAL to TCM-3



Late Cruise

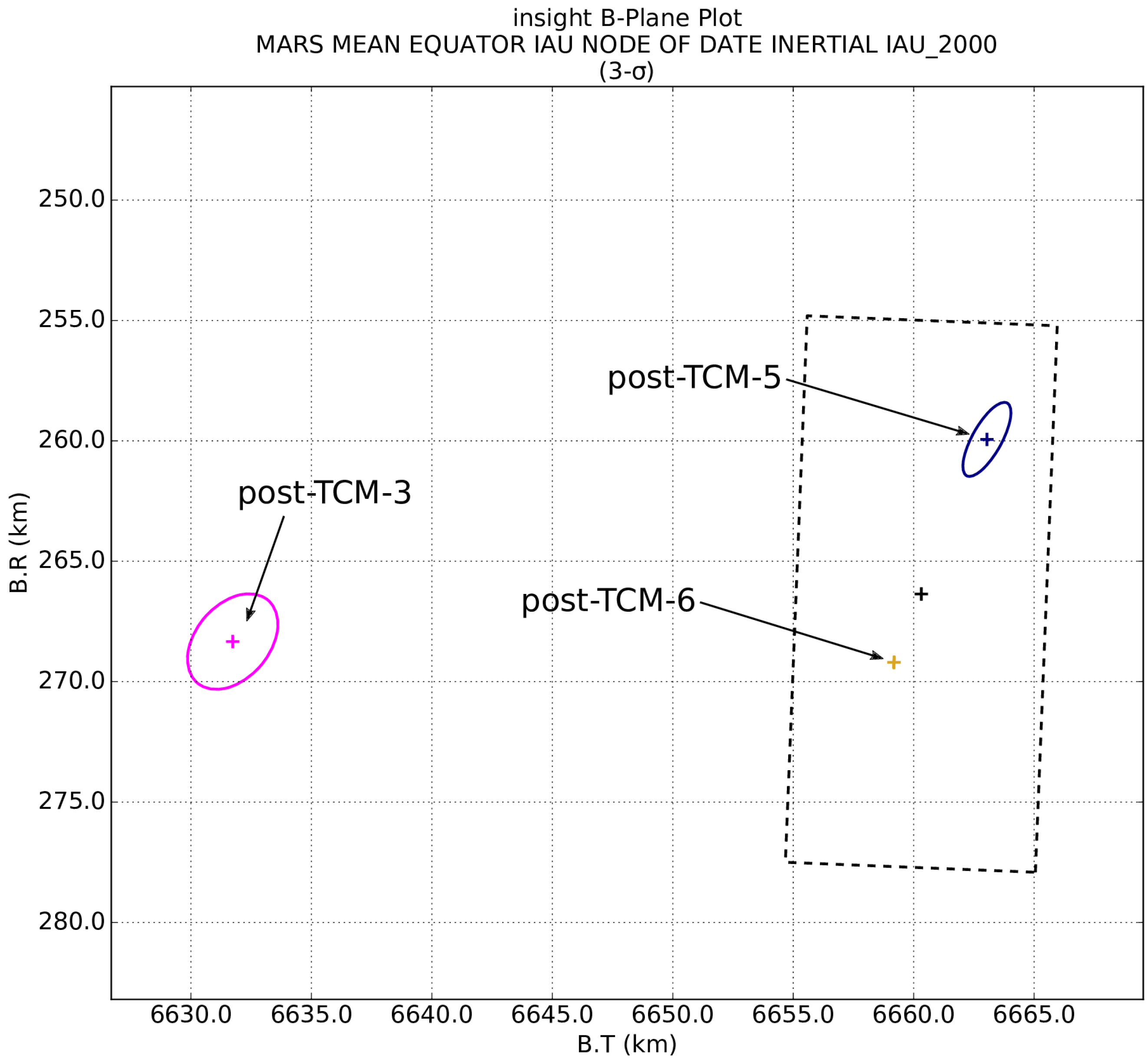
- Outgassing subsided, calm period to fine-tune approach
- TCM-4 was cancelled
  - We still needed a maneuver to meet requirements
  - At the TCM-4 epoch, the necessary correction was too small to be worthwhile
  - Fixed errors are large on this spacecraft because of slews



Cold Reboot

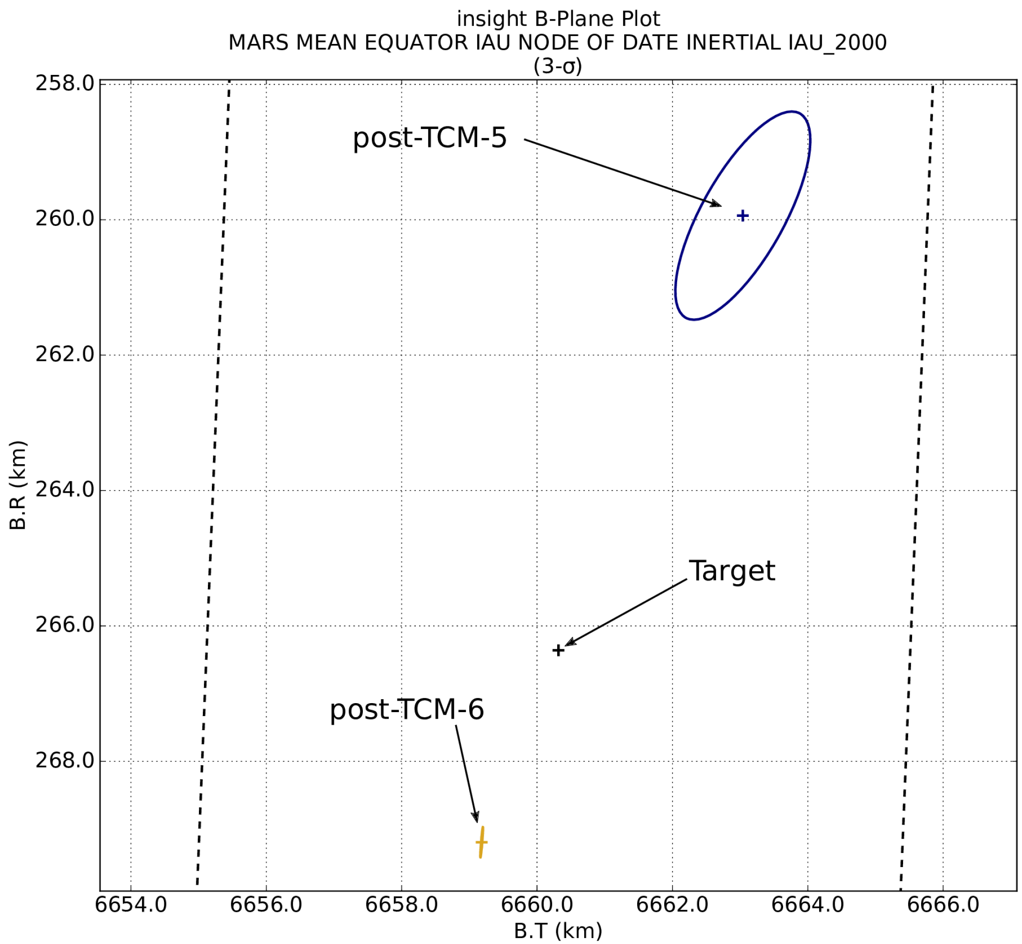
- One month before EDL
- Want to put spacecraft in clean, known state
- InSight boots into safe mode → RCS firings guaranteed
- Predicted 10 mm/s to 30 mm/s; got 21 mm/s

B-plane: TCM-3 to Entry



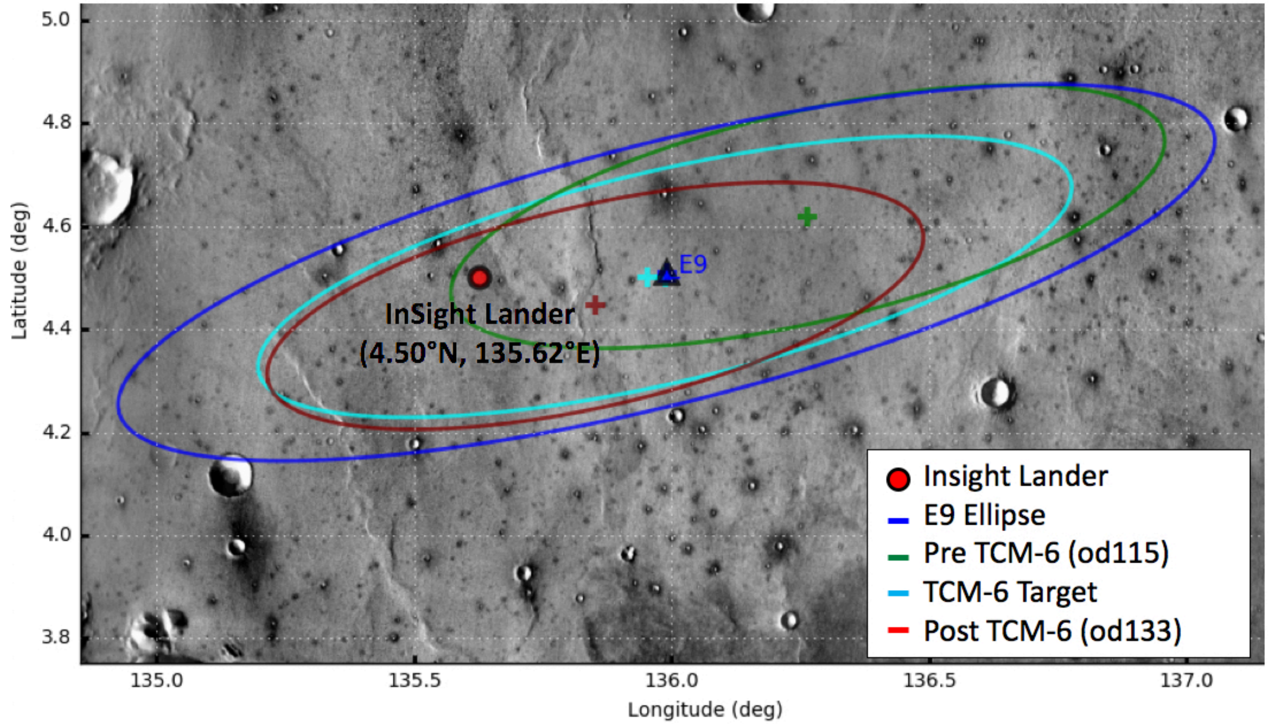
Final Approach

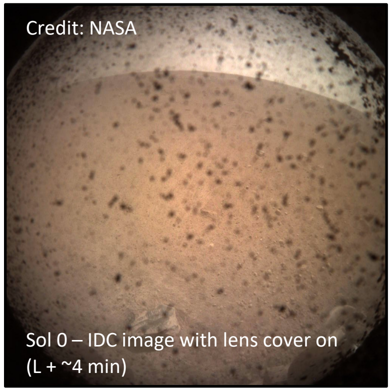
- OD/navigation goal: deliver InSight accurately to the target
- TCM-6 was not needed for NAV or EDL requirements
- Project chose to implement TCM-6 to avoid potential ground hazards

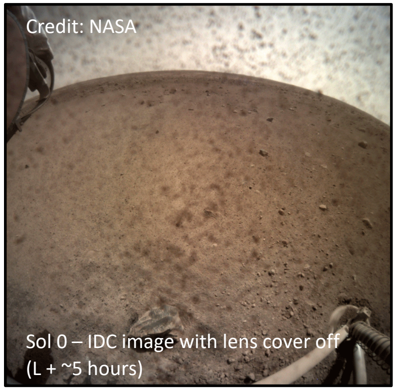


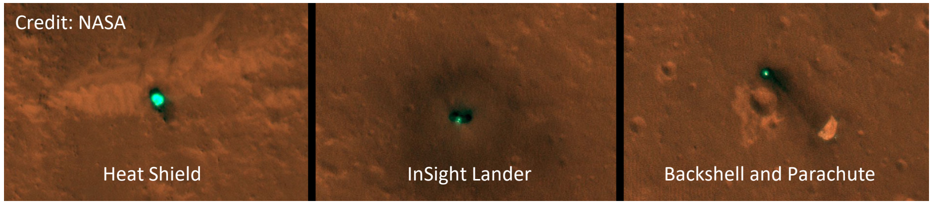
Landing Accuracy

- On 12/06/18, MRO acquired HiRISE and Context (CTX) images which showed the final location of the InSight lander, the backshell/parachute, and the heat shield
- The lander is about 13.8 km away from the target
  - The heat shield is located 0.762 km down-track (northeast) from the lander and the backshell/parachute is located 0.553 km in the southeast direction









InSight Lands on Mars!

- Data confirming nominal touchdown was received at 11:52:59 AM PST!

InSight Navigation Team

- InSight Navigation Team: Allen Halsell (NTC), Eric Gustafson, Fernando Abilleira, Gene Bonfiglio, Min-Kun Chung, Yungsun Hahn, Dan Jamerson, David Jefferson, Gerhard Kruizinga, Eunice Lau, Jules Lee, Sarah Elizabeth McCandless, Neil Mottinger, Evgeniy Sklyanskiy, Mark Wallace

Want to learn more?

- InSight Special Session at AAS/AIAA Space Flight Mechanics meeting (Jan. 2019):
  - *2018 InSight Trajectory Reconstruction and Performance from Launch through Landing* (Fernando Abilleira)
  - *Mars Reconnaissance Orbiter Navigation Strategy for Support of InSight Lander's Entry, Descent and Landing Sequence* (Premkumar Menon)
  - InSight Orbit Determination (Eric Gustafson)
  - *InSight Attitude Control System Thruster Characterization and Calibration for Successful Navigation to Mars* (Jill Seubert)
  - *Navigation Performance of the 2018 InSight Mars Lander Mission* (Allen Halsell)
  - *Maneuver Design Overview of the 2018 InSight Mars Lander Mission* (Min-Kun Chung)
  - *Mars Reconnaissance Orbiter Maneuver Plan for Mars 2020 Entry, Descent, and Landing Support and Beyond* (Sean Wagner)
  - *Atmospheric Impacts on EDL Maneuver Targeting for the Insight Mission and Unguided Mars Landers* (Eugene Bonfiglio)
  - *Orbiters, Cubesats, and Radio Telescopes, Oh My; Entry, Descent, and Landing Communications for the 2018 InSight Mars Lander Mission* (Mark Wallace)

Acknowledgements

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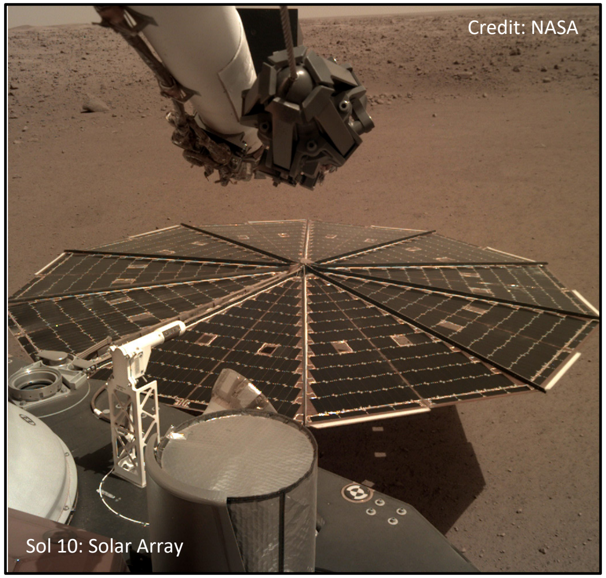
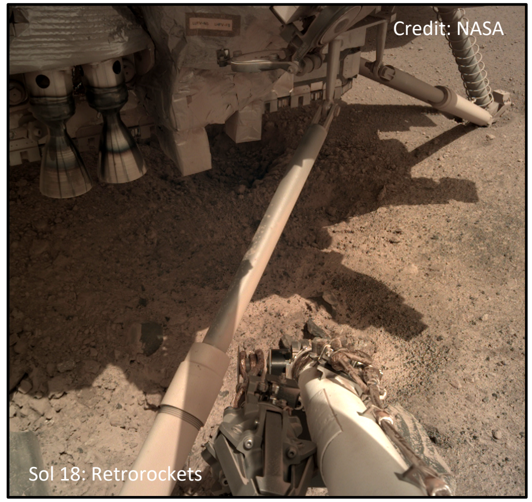
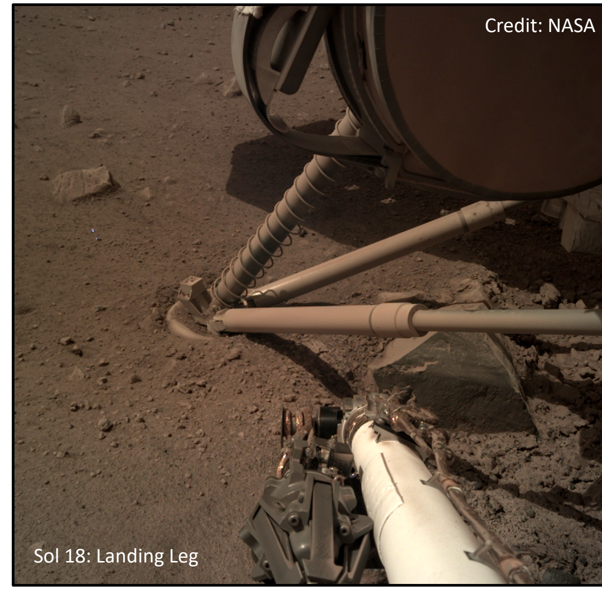
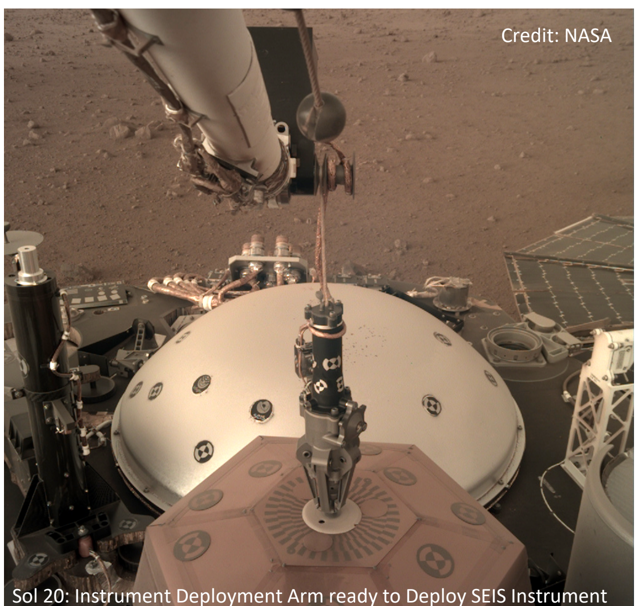
InSight

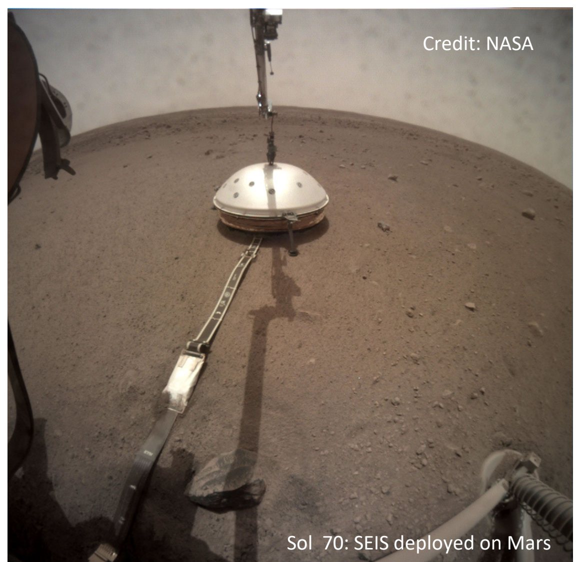
Questions?

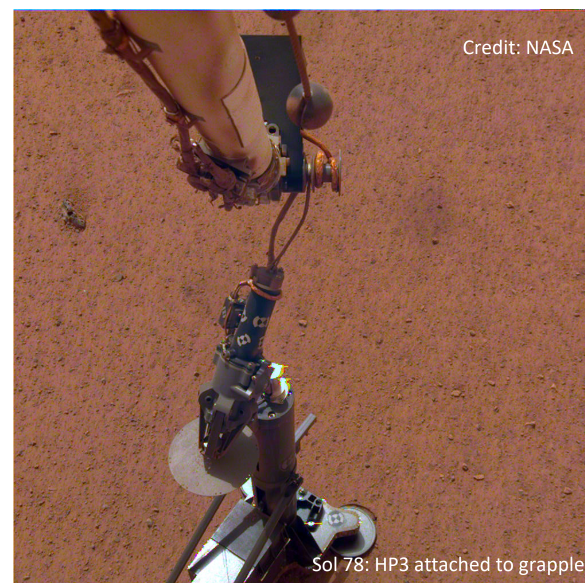

Credit: NASA
Sol 10: Solar Array


Credit: NASA
Sol 18: Retrorockets


Credit: NASA
Sol 18: Landing Leg

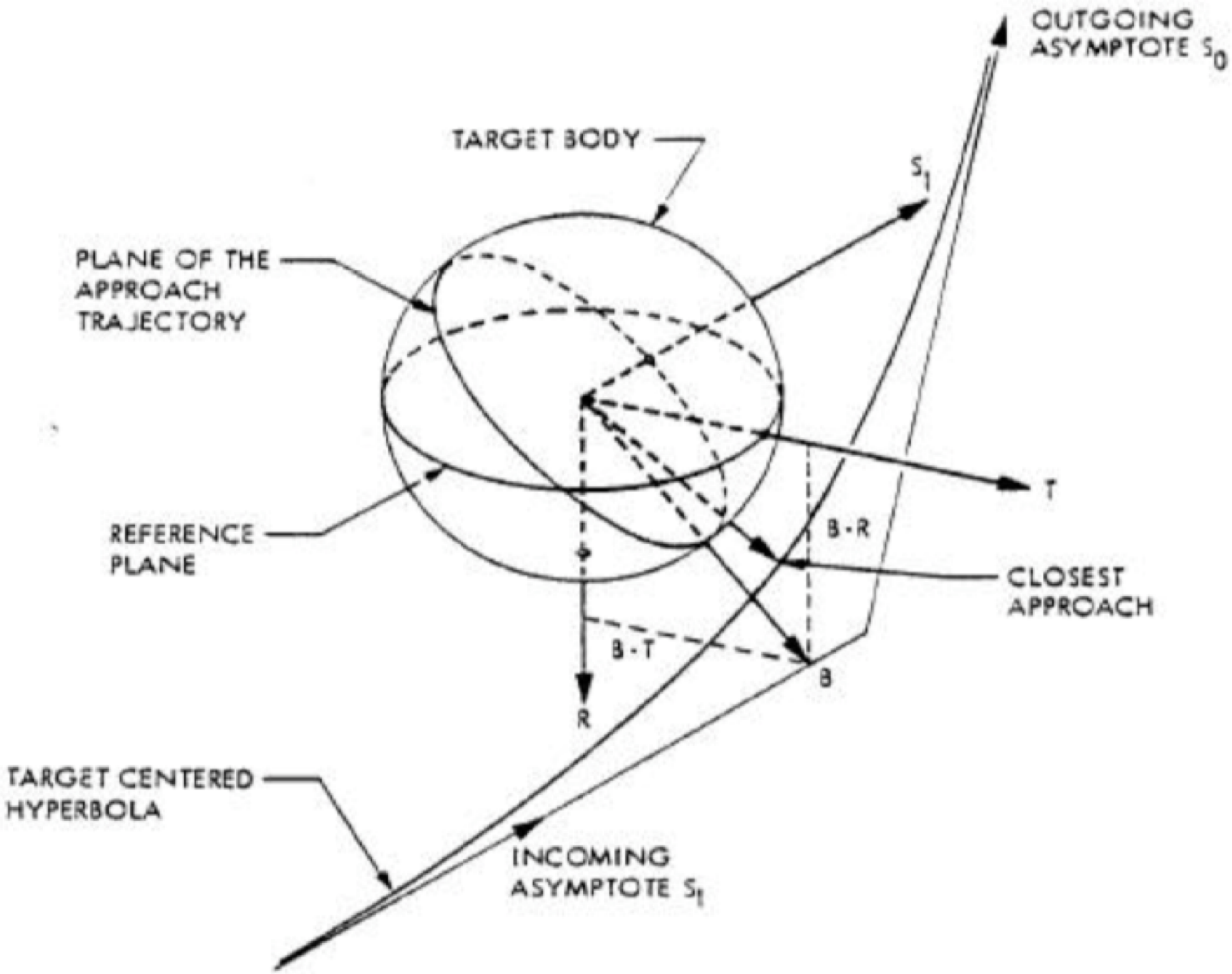

Credit: NASA
Sol 20: Instrument Deployment Arm ready to Deploy SEIS Instrument


Credit: NASA
Sol 70: SEIS deployed on Mars


Credit: NASA
Sol 78: HP3 attached to grapple

Backup Slides

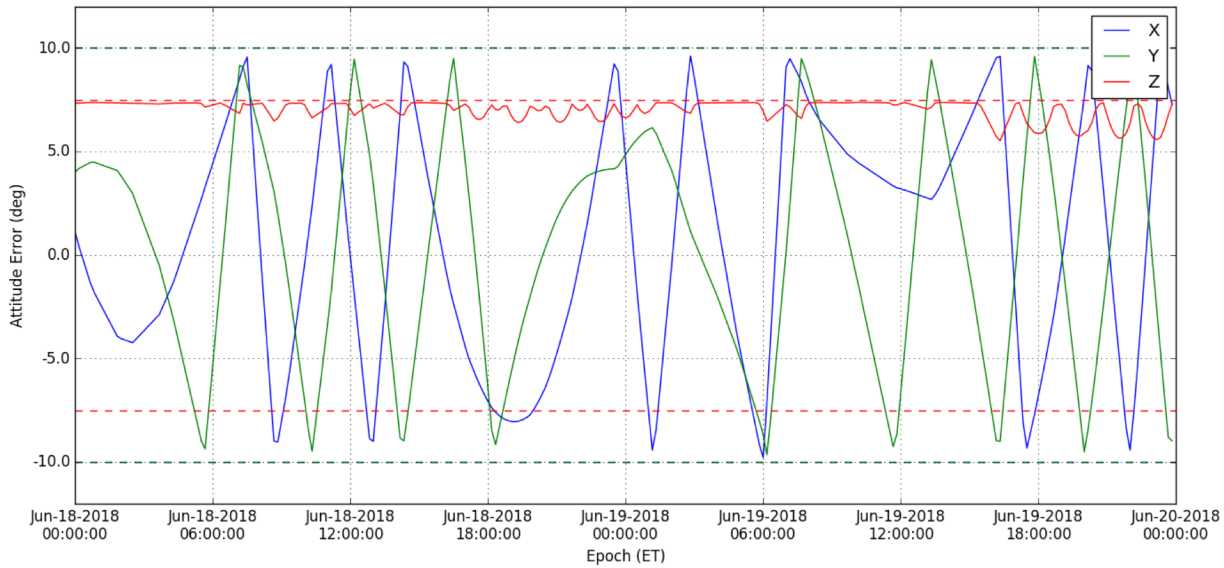
B-Plane Definition



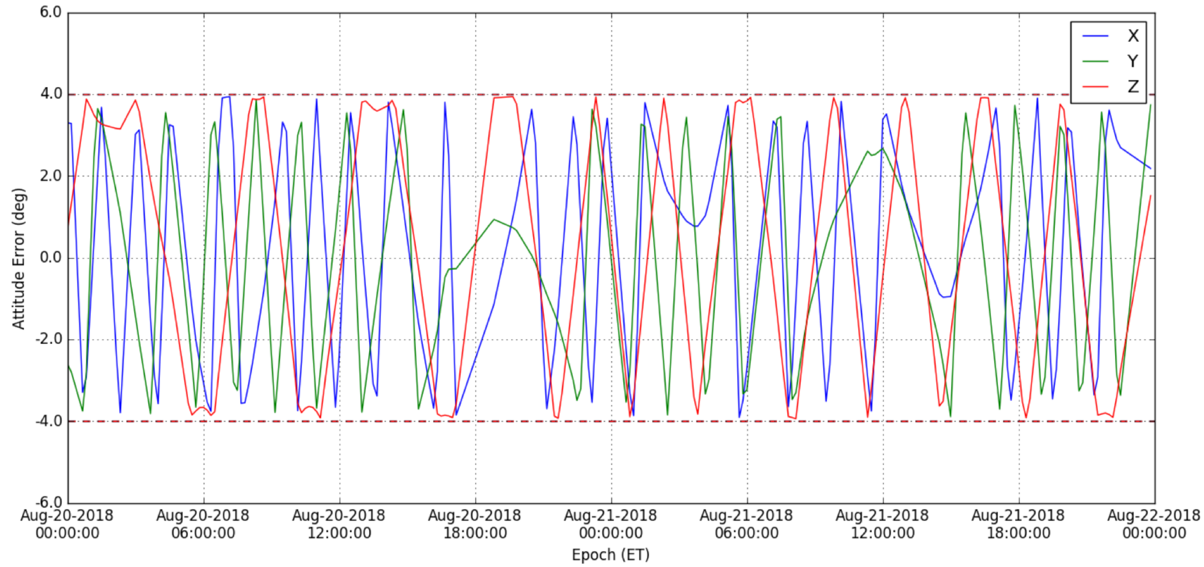
Moriba Jah, “Derivation of the B-Plane (Body Plane) and its Associated Parameters.”

Attitude Errors During Nominal Cruise Ops

- Early cruise:
  - Solar torque due to off-Sun pointing pinned spacecraft against +Z deadband
  - Drifts between ±X and ±Y limits



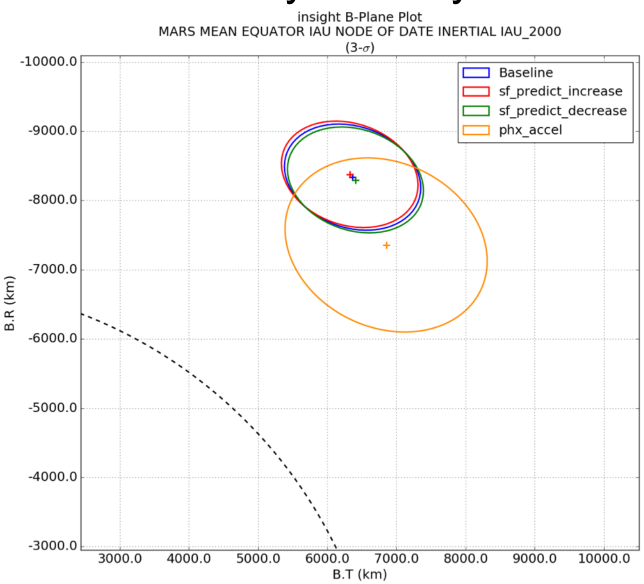
- Late cruise:
  - Solar torque balanced as solar arrays ~ Sun-pointed
  - Drifts between ±X, ± Y, ± Z limits



Small Force Model Comparisons

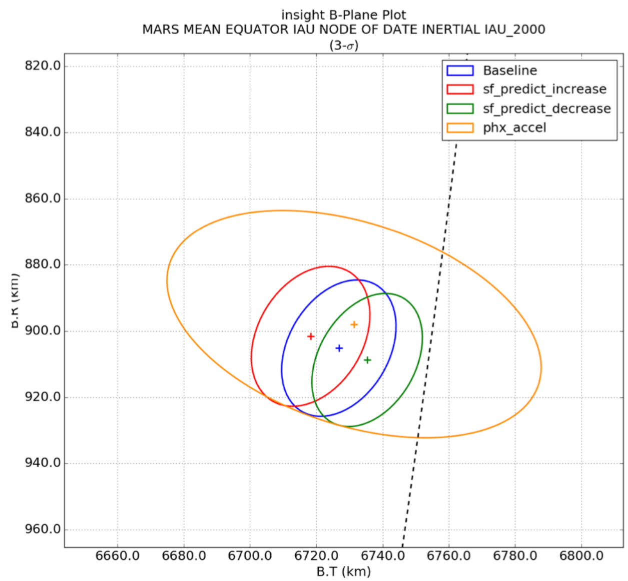
- Various predictive models compared throughout cruise to assess suitability of baseline approach
- Impact of small force prediction proportional to “time to go”

TCM-2 DCO
Entry-142 days



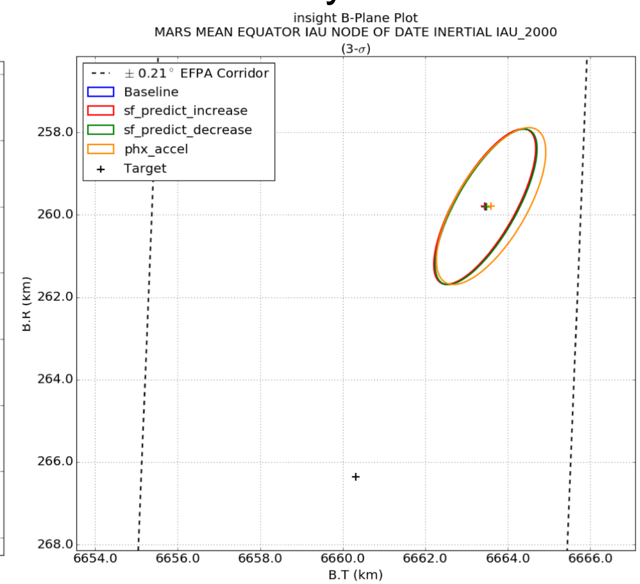
- Solution uncertainty driven by data uncertainties
- Phoenix model > 3**σ** away from baseline

TCM-3 DCO
Entry-50 days



- Solution uncertainty driven by small force model
- ±5% acceleration shifts solution by 2**σ**

TCM-6 DCO
Entry-48 hrs



- Short propagation time renders models indistinguishable

Cruise TCM Summary

Event	Location	Date (UTC, 2018)	Magnitude (m/s)	Objective
TCM-1	L + 17d	May 22	3.78	Remove most of injection errors
TCM-2	E - 121d	July 28	1.50	Correct for TCM-1 and orbit determination errors
TCM-3	E - 45d	Oct. 12	0.167	Correct for TCM-2 and orbit determination errors. All subsequent TCMs target to desired landing site
TCM-4	E - 15d	Nov. 1	Cancelled	Correct for orbit determination and TCM-3 execution errors
TCM-5	E - 8d	Nov. 18	0.057	Correct for orbit determination and TCM-4 execution errors
TCM-5X	E - 5d	Nov. 21	N/A	Contingency - Same objectives as TCM-5.
TCM-6	E - 22h	Nov. 25 21:40	0.085	Final targeting to landing site.
TCM-6X	E - 8h	Nov. 26 11:40	N/A	Contingency – In case TCM-6 cannot be executed
TCM-6XM	E - 8h	Nov. 26 11:40	N/A	Contingency – If TCM-6 aborts or safes. Selected from pre-determined menu of validated maneuvers to maximize the probability of successful landing.

TCM-6 Design

- TCM-5 and TCM-6 were only 7 days apart, but it takes time and data to reconstruct maneuvers